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MICROSTRUCTURE AND TENSILE STRENGTH OF FRICTION STIR WELDING OF AL-CU

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ABSTRACT

Friction Stir Welding (FSW) is a relatively new solid state joining technique which is used not only for joining the aluminium and its alloys but also has potential for joining dissimilar materials with very different physical and mechanical properties that are hard to weld using conventional fusion welding processes. FSW of aluminium and its alloys, and other similar material joining have now been commercialised in the automotive, aerospace, and marine industries; and recent interest is focused on joining dissimilar materials in developing effective manufacturing processes based on friction stir welding for electrical connecting and terminal products. There have been a reasonable number of studies in the literature on microstructure and fracture behaviour under static loading and very few studies on cyclic loading of FSW of dissimilar materials. However, a better scientific understanding in a number of aspects is required. This include interface phenomena during FSW of dissimilar materials with large differences in melting temperatures, how exactly the microstructure in the interfacial region is related to fracture behaviour when subjected to static is far from being fully understood. Thus, this study aims to understand the joint formation and the effect of interface microstructure on fracture behaviour under static and cyclic loading and how the FSW parameters affect the interface microstructure and fracture behaviour during FSW of dissimilar materials.

KEYWORDS: Friction Stir welding, Interface microstructure, Dissimilar Metals, Tensile Strength, Intermetallic Compounds

INTRODUCTION

Friction Stir Welding

As introduced previously, Friction stir welding (FSW) is a solid state welding process invented and patented by The Welding Institute (TWI) in 1991, for butt and lap welding of ferrous and non-ferrous materials and plastics [1]. FS welding is conceptually very simple; a non-consumable specific shaped rotating tool with (threaded) pin is plunged and traversed along the joint line between the work pieces to be welded which locally plasticises the work-piece due to frictional heating. The plasticised material is transported around and deposited behind the tool to form a solid-phase joint (Figure 1). There are two sides with respect to the welding tool during FSW. The advancing side (AS) is the side where the tool rotational motion and traverse direction are in the same direction, and the retreating side (RS) is the side where the tool rotational motion is opposite to the traverse direction. Although conceptually simple, FS science is highly complex. Many physical phenomena during FSW where the material experiences very high strain ($\mathcal{E}$) and strain rate ($d\mathcal{E}/dt$) in a varying temperature (T) field and the subsequent macro/microstructures and properties of FSW dissimilar materials have been studied very intensively.

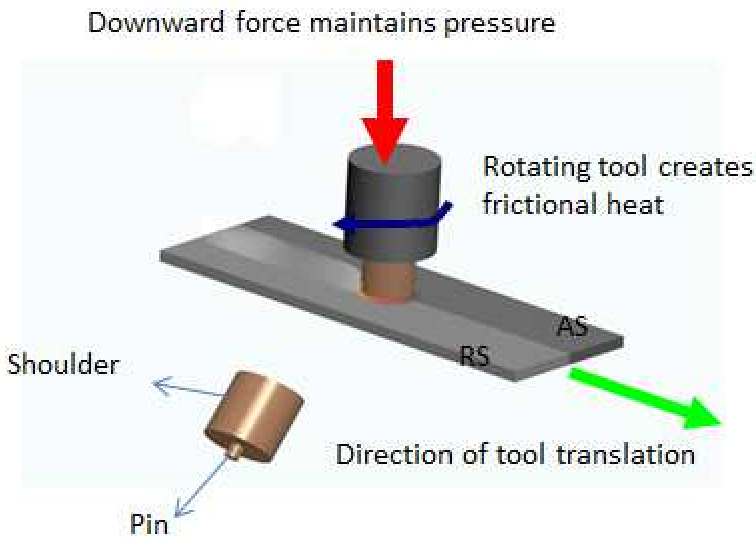


Figure 1: Schematic Illustration of FS Welding Process

In general, it is well known that fusion welding of one metallic alloy to another with considerably higher melting temperatures (referred to as a large $\Delta T_{Melting}$ couple, such as Al to steel, Al to Ti or Al to Cu) is important in many industries but are very challenging [2-8] due to physical mismatches such as differences in melting temperature, thermal expansion and thermal conductivity can make the joining almost impractical using conventional welding techniques. Formation of thick intermetallic layers (due to high heat input and liquation of aluminium) is known to deteriorate mechanical properties of the joints [3].It is essential to develop more reliable joining procedures than those currently available for dissimilar metal joints. Therefore development of FSW as a solid-state joining process is of high importance from both scientific and industrial point of view. As FSW is a solid-state joining process (material does not melt during the process), it is free from solidification-related defects associated with fusion welding such as solidification cracking and porosity. Also, this process requires less energy compared to conventional fusion welding techniques, hence lower heat input is transferred to the work piece which reduces distortion. Compared to fusion welding techniques, FSW does not require shielding gas/flux, thus making it more environmentally friendly. Moreover, during FSW dynamic recrystallization will occur in the stir zone due to the significant frictional heating and intensive plastic deformation (induced by the rotating pin), which results in the formation of fine and equiaxed recrystallized grains. The formation of a recrystallized fine grain microstructure in weld results in improved mechanical properties such as higher joint fracture strength and fatigue resistance.

In FS welding of a large $\Delta T_{Melting}$ couple, aided by frictional and deformation heat, metallurgical bond is established through diffusion and subsequent formation of interfacial intermetallic. It is clear that a metallurgical bond is a condition for a quality joint and a metallurgical bond implies low electric resistance, although intermetallics are commonly viewed to affect joint strength adversely. The cited studies on FS Al-to-Cu [9-14, 16, 18, 19 and 26-33] are basically the initial work showing FS Al-to-Cu weld able, providing detailed metallurgical analysis for understanding the interface microstructure and relating to properties.

We can discuss using a lap joint example shown in Figure 2. The process of conducting FSW in lap joint configuration is called friction stir lap welding (FSLW.)The discussion is also valid for butt joint. If the top and bottom pieces are similar alloys, FSW flow/deformation results in a complete mix in the stir zone, then the two pieces become one.

The joining mechanism in FS large $\Delta T_{Melting}$ couple is however fundamentally different. Large $\Delta T_{Melting}$ results in the bottom piece plasticised no longer if the top is or in melting of the top piece if the bottom plasticises. A joint forms through alloying at the interface, as a result of diffusion and then intermetallic formation. Achieving continuity and high strength in FS joints of large $\Delta T_{Melting}$ couples has increasingly been the topic of many recent studies including those on FS Al-to-Cu [9-14, 16, 18, 19 and 26-33]. It is clear that a metallurgical bond is a condition for a quality joint, but intermetallics have been commonly viewed to adversely affect joint strength. The recent FSW Al-to-Cu studies have demonstrated the couple being FS weld able and interface microstructures in various FSW conditions have been studied and revealed.

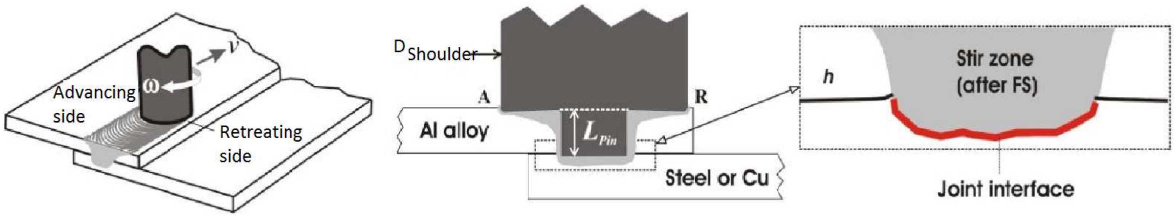


Figure 2: Schematic Illustration of FSL Welding

Experimental Procedure

A series of FSLW experiment will be conducted using FV200 milling machine, to investigate the various pin positioning (D_p) and speed conditions (ω, v) which are the influential parameters for Nucleation/intermetallics growth at the Al-Cu interface. Al 6060-T5 (300x100x6mm) placed on the advancing side and top of the and pure Cu on the retreating side (300x100x1.4mm) work pieces were FSL welded with 1400 rpm as a rotational speed, 40mm/min as a traverse speed,3 degrees of tilt angle and tool pin penetration of close to 0 mm and 0.4 mm respectively from the top surface of the bottom plate. K-type thermocouple will be used to measure the FSLW interface temperature. This addresses the research question one. The results from the experiments will help to further understand the interface microstructure at Al-Cu and Al-steel FSLW for various tool positioning and speed condition. Table 1 represents the conditions for the experiment. Metallographic samples were mounted and polished, and etched with modified Keller's reagent. Microstructures at the interface of FSLW dissimilar metals (Al-Cu) were observed in SEM/EDS analysis were conducted. After FSLW of Al-Cu experiments conducted for the various tool positioning and speed conditions, samples were taken to the tensile testing. Tensile test samples and supporting pieces were 16mm wide, samples were tested at a constant crosshead displacement rate of 3mm/min using 50KN Tinus Olsen tensile testing machine (Fig 6)

Table 1: Details of FSLW Parameters and the Materials Used to Conduct the Experiment

Parameters	Values
Plate thickness	Al6060-T5-6mm, Cu-3mm
Rotational speed (ω)	1400 rpm
Welding Speed (v)	40mm/min
Shoulder diameter	18mm
Pin diameter and length	6mm and 6mm
Pin Penetration	6.4mm (or 0 & 0.4mm)
Tensile specimen width	16 mm
TS strength (maximum)	448 N/mm

RESULTS AND DISCUSSIONS

Effect of Tool Positioning on Interface Microstructure

Typical Al-Cu interfaces of the welds made using Dp≈0 are shown by SEM micrographs in Figure 3a. There is no particular feature along the interface (no intermetallic compounds). In the sample made using Dp =0.4 mm, continuous intermetallic compounds can be observed along the interface, as shown in Figure 3b.

An EDS spectrum analysis for different locations in FSLW interface Al-Cu shown in Figure 4. EDS spectrum from a point analysis on an outburst is shown in Figure 5 and there is not an oxygen peak suggesting that these intermetallic compounds are not oxides. Rather they should be Al-Cu intermetallic compounds. The same form of local outbursts at the interface resulting from the early stage of interfacial intermetallic growth in solid Al-cu couples has commonly been observed [9-17].

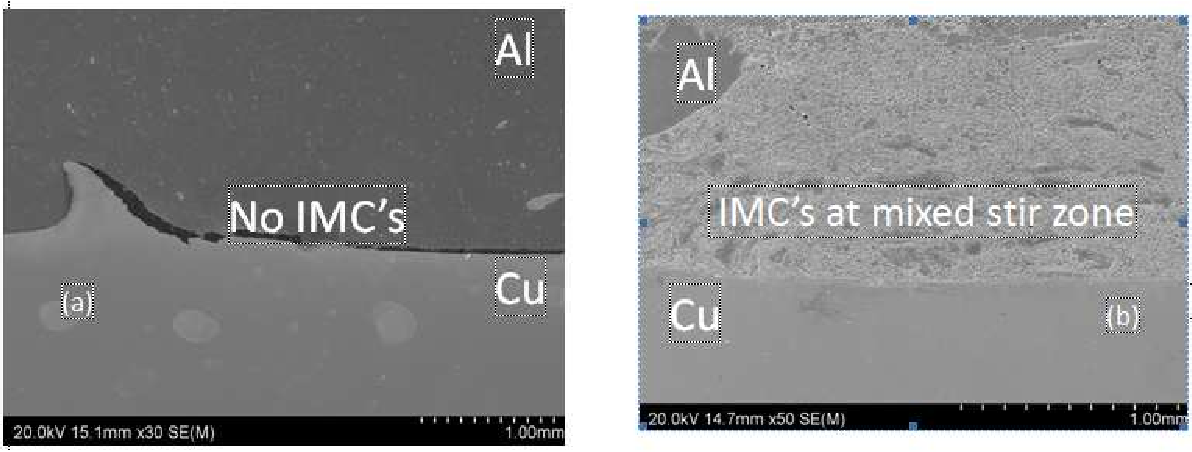


Figure 3: Interface Micro Features Shown by SEM Micrographs Taken in Welds Made with A Dp ≈0 Mm, B Dp>0 (0.4) Mm Displaying Intermetallic Compounds

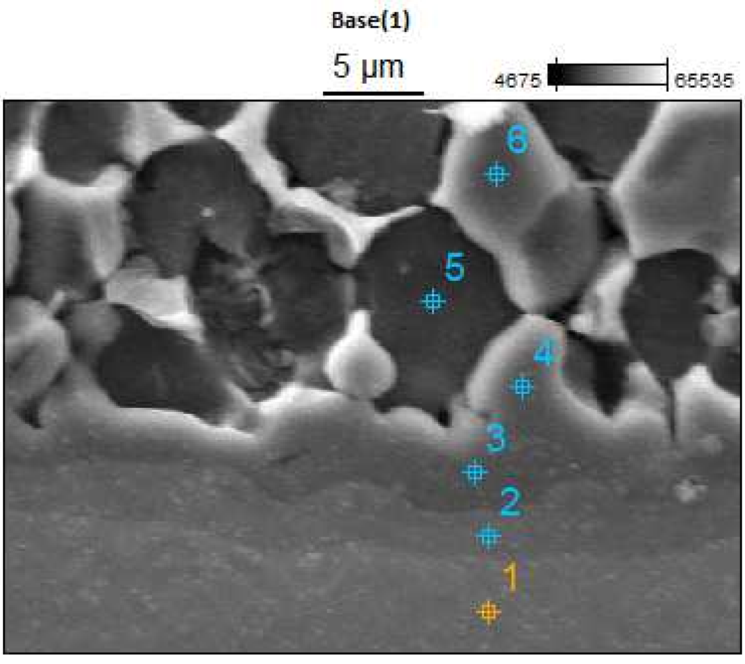
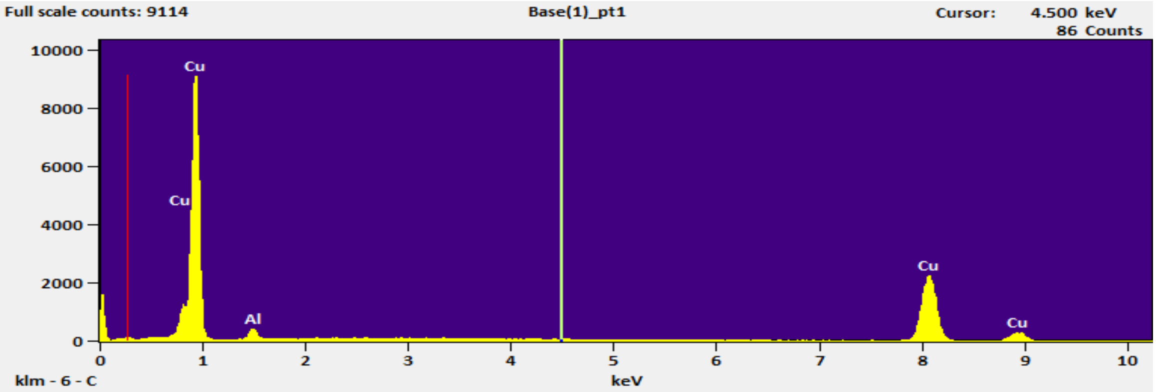


Figure 4: SEM/EDS Spectrum from a Point Analysis at Al-Cu Interface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Base(1)_pt1
Cursor: 4.500 keV
86 Counts
Cu
Cu
Al
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klm - 6 - C
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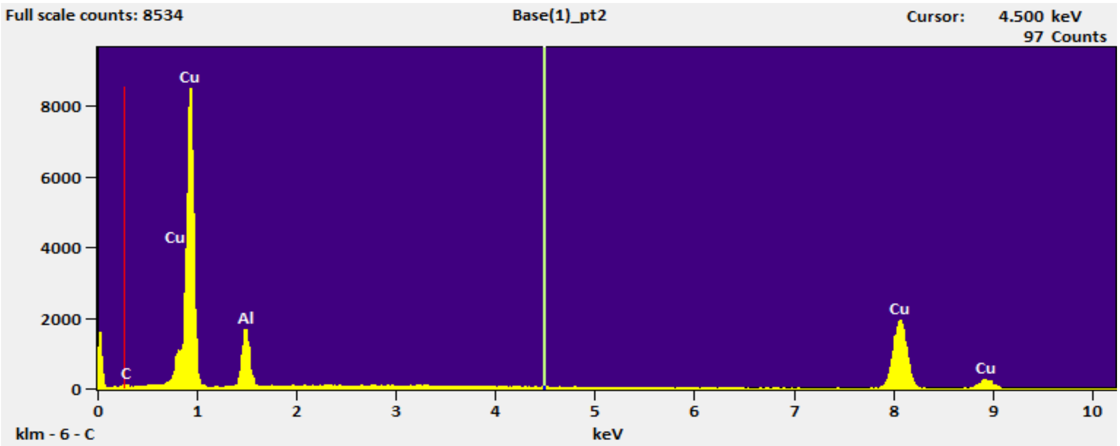
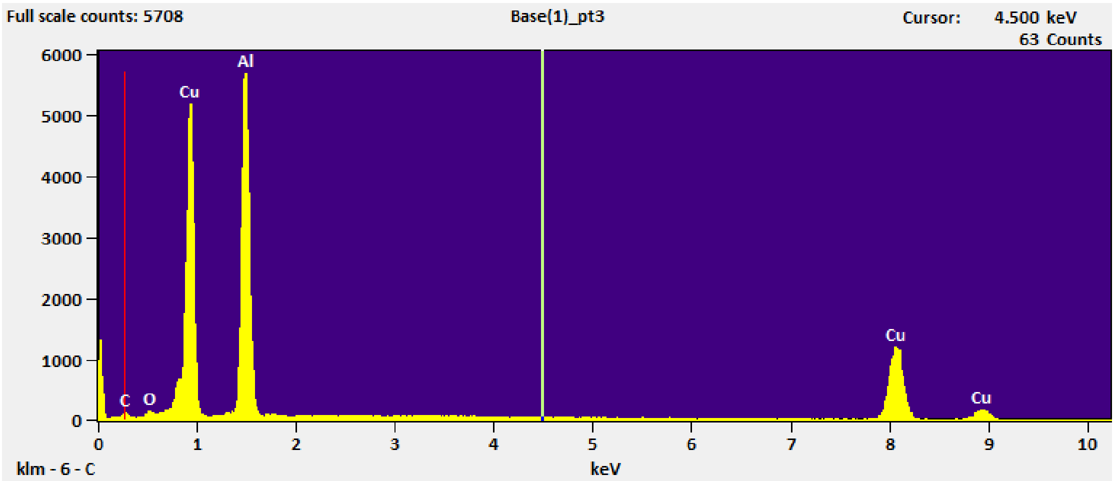
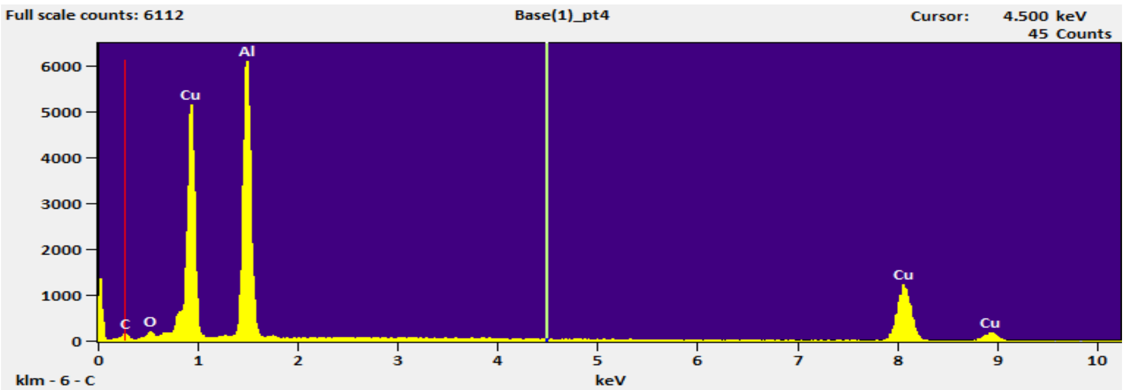
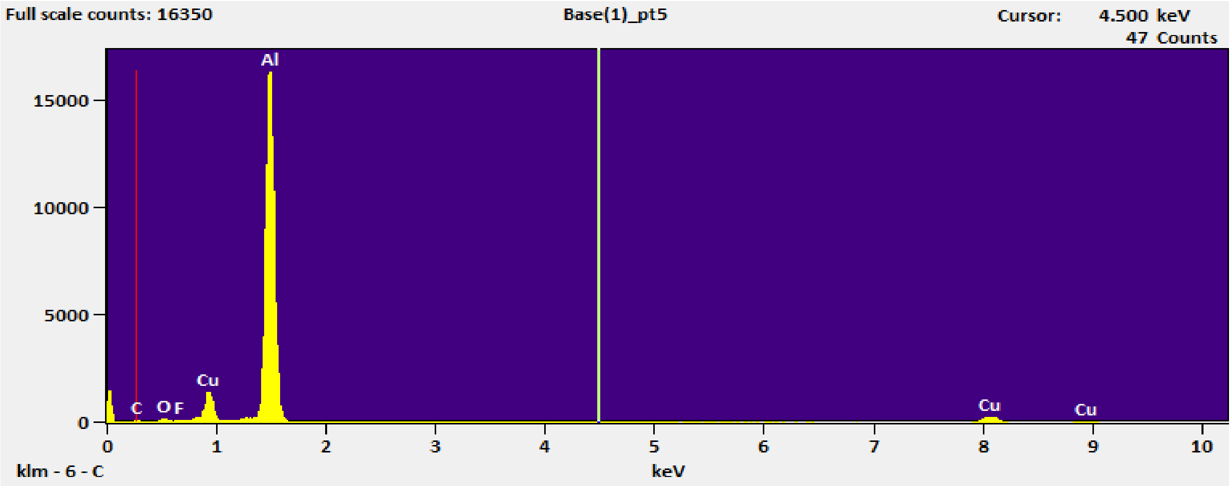

Full scale counts: 8534
Base(1)_pt2
Cursor: 4.500 keV
97 Counts
Cu
Cu
Al
C
Cu
Cu
klm - 6 - C
keV


Full scale counts: 5708
Base(1)_pt3
Cursor: 4.500 keV
63 Counts
Al
Cu
C
O
Cu
Cu
klm - 6 - C
keV


Full scale counts: 6112
Base(1)_pt4
Cursor: 4.500 keV
45 Counts
Al
Cu
C
O
Cu
Cu
klm - 6 - C
keV



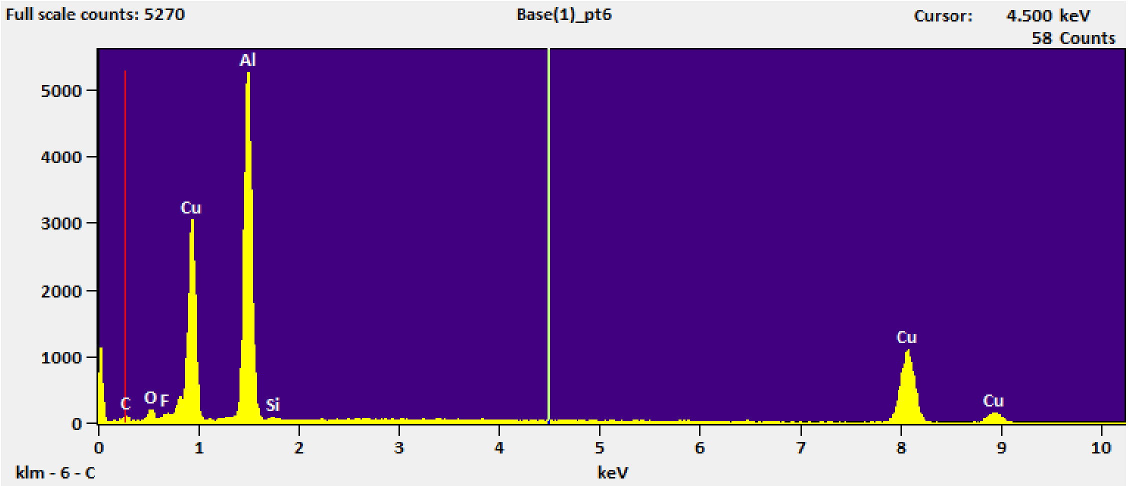
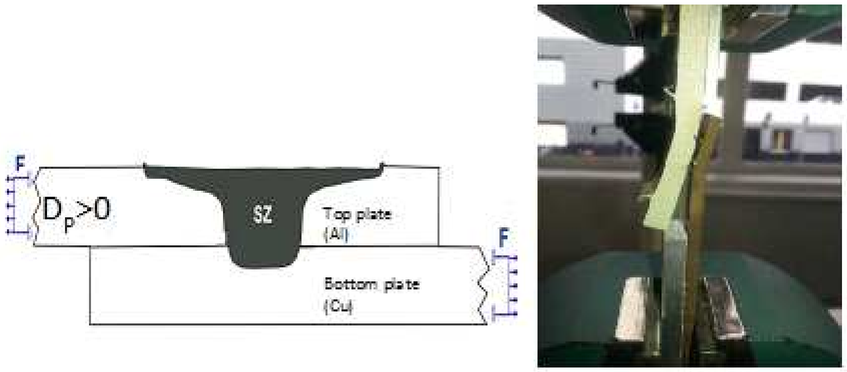


Figure 5: SEM/EDS Spectrum from a Point Analysis at Different Positions in Al-Cu Interface

No intermetallic compounds formed for the tool positioning Dp≈0 for FSLW of Al-Cu, but for Dp> 0 (=0.4), there is an irregular or discontinuous intermetallic compounds observed at both the Al-Cu FSLW interface.

Effect of Dp-Dependent Interface Microstructure on Fracture Strength

(a)



(b)

Figure 6: Images of Tensile Tested Samples of FSL Weld of Al-Cu, (a) Dp≈0 No local Bending (b) Dp> 0 (=0.4) Sample Showing Local Bending Before Fracture

The tensile strength obtained for FSLW of Al-Cu for Dp≈0 is zero (0 N/mm) (Figure 6 a), but the Tensile strength of FSLW Al-Cu for Dp> 0 (=0.4) is equal to 400-450 N/mm (Figure 6b).

CONCLUSIONS

Tensile strength of Al-Cu FSLW obtained for Dp≈0 is 0 N/mm, and the tensile strength obtained for Dp>0 ranges from 400-450 N/mm which is very high strength values compared to previous studies. This is due to local bending offered by the high ductility of the Al FCC structure thus reorientating to reduce considerably the stress concentration.

REFERENCES

1. Thomas W M, Nicholas ED, Needham JC, Murch MG, Templesmith P, Dawes CJ. *Improvements relating to Friction Welding. International Patent Application*, PCT/GB92/02203 (Patent) December 1991.

2. Mishra RS, Ma ZY. Friction stir welding and processing. *Materials Science and Engineering R.* 2005; *50:* p1-78.

3. R.S. Mishra and M.W. Mahoney (edited), “Friction stir welding and processing”, ASM International, Materials Park, Ohio, 2007 (360 pages).

4. R. Nandan, T. DebRoy and H.K.D.H. Bhadeshia, “Recent advances in friction-stir welding – process, weldment structure and properties”, Progress in Materials Science 53 (2008) 980-1023.

5. P.L. Threadgill, A.J. Leonard, H.R. Shercliff and P.J. Withers, “Friction stir welding of aluminium alloys”, International Materials Review 54 (2009) 50-93.

6. L.E. Murr, “A review of FSW research on dissimilar metal and alloy systems”, Journal of Materials Engineering and Performance 19 (2010) 1071-1098.

7. D. Lohwasser and Z.W. Chen (edited), “Friction Stir Welding – from basics to applications”, (ISBN 978-1-84569-450-0) Woodhead Publishing Ltd, Cambridge, and CRC Press, Roca Raton, 2010 (424 pages).

8. R. Rai, A. De, H.K.D.H. Bhadeshia and T. DebRoy, “Review: friction stir welding tools”, Science and Technology of Welding and Joining 16 (2011) 325-342.

9. Galvão 1,, D. Verdera 2, D. Gesto 2, A. Loureiro 1 D. M. Rodrigues 1, "ANALYSING THE CHALLENGE OF ALUMINIUM TO COPPER FSW", CEMUC, Department of Mechanical Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal 2 AIMEN, Relva 27A Torneiros, 36410 Porriño, Spain
10. Ahmed. ELREFAEY, Makoto. TAKAHASHI and Kenji IKEUCHI, " Microstructure of aluminium/copper lap joint by friction stir welding and its performance", Joining and Welding Research. Osaka University (11-1 Mihogaoka , Ibaraki, Osaka 567-0047, Japan).
11. A. Elrefaey, M. Takahashi and K. Ikeuchi, "Preliminary investigation of friction stir welding aluminium/copper lap joints", Welding in the world 49 (2005) 93-101.
12. A. Abdollah-Zadeh, T. Saeid and B. Sazgari, "Micro structural and mechanical properties of friction stir welded aluminium/copper lap joints", Journal of Alloys and Compounds 460 (2008) 535-538.
13. T. Saeid, A. A. Abdollah-Zadeh and B. Sazgari, "Weldability and mechanical properties of dissimilar aluminium-copper lap joints made by friction stir welding", Journal of Alloys and Compounds 490 (2010) 652-655.
14. P. Xue, B.L. Xiao, D. Wang and Z.Y. Ma, "Achieving high property friction stir welded aluminium/copper lap joint at low heat input", Science and Technology of Welding and Joining 16 (2011) 657-661.
15. M Satya Narayana Gupta, B Balunaik and KGK Murti, " Effect of tool geometry on joint properties of friction stir welded Al/Cu bimetallic lap joints", The IUP Journal of Mechanical Engineering 1 (2012) 38-50.
16. VAHID FIROUZDOR and SINDO KOU, " Al-to-Cu Friction stir lap welding", Metallurgical and Materials Transactions A 43 (2012) 303-315
17. MOSTAFA AKBARI and REZA ABDI BEHNAGH, "Dissimilar Friction- Stir Lap joining of 5083 Aluminium Alloy to CuZn34 Brass", Metallurgical and Materials Transactions B 43B (2012) 1177-1186
18. P. Xue, B.L. Xiao, D. Wang and Z.Y. Ma, "Enhanced mechanical properties of friction stir welded dissimilar Al-Cu joint by intermetallic compounds", Materials Science and Engineering A 527 (2010) 5723-5727.
19. P. Xue, B.L. Xiao, D. Wang and Z.Y. Ma, "Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al-Cu joints", Materials Science and Engineering A 528 (2011) 4683-4689.
20. Colliagan, K., 1999, "Dynamic material deformation during Friction Stir Welding of aluminium," The 1st International symposium on Friction Stir Welding CA, USA.
21. Bus-bar. Available from: http://en.wikipedia.org/wiki/Bus-bar
22. Design Considerations. Available from: http://www.copperinfo.co.uk/busbars/pub22-copper-for-bus-bars/sec1.htm.
23. ASM Metals Handbook: properties and selection of nonferrous alloys and special purpose materials. Vol. 2. 1991, ASM Internationa .
24. Zorc TB, Reidenbach F, Sobie NM. Harrison LA (eds.) ASM Handbook Welding, brazing and soldering. Vol 6. ASM International, USA; 1993.

25. [25] O'Brien A, Guzman C (eds.) American Welding Society, Welding Handbook Welding Processes, part 2volume 3 Ninth Edition Miami: American Welding Society; 2007.
26. T. DebRoy and H.K.D.H. Bhadeshia, "Friction stir welding of dissimilar alloys – perspective", Science and Technology of Welding and Joining 15 (2010) 266-270.
27. J. Ouyang, E. Yarrapareddy and R. Kovacevic, "Micro structural evolution in the friction stir welded 6061 aluminium alloy (T6-temper condition) to copper", Journal of Materials Processing Technology 172 (2006) 110-172.
28. A. Esmaeili, M.K. Besharati Givi and H.R. Zareie Rajani, "A metallurgical and mechanical study on dissimilar friction stir welding of aluminium 1050 to brass (CuZn30)", Materials Science and Engineering A 528 (2011) 7093-7102.
29. A. Esmaeili, H.R. Zareie Rajani, M. Sharbati, M.K. Besharati Givi and M. Shamanian, "The role of rotation speed on intermetallic compounds formation and mechanical behaviour of friction stir welded brass/aluminium 1050 couple"Intermetallics 19 (2011) 1711-1719.
30. H.J. Liu, J.J. Shen, L. Zhou, Y.Q. Zhao, C. Liu and L.K. Kuang, "Micro structural characterisation and mechanical properties of friction stir welded joints of aluminium alloy to copper", Science and Technology of Welding and Joining 16 (2011) 92-99.
31. I. Galvao, J.C. Oliveira, A. Loureiro and D.M. Rodrigues, "Formation and distribution of brittle structures in friction stir welding of aluminium and copper: influence of process parameters", Science and Technology of Welding and Joining 16 (2011) 681-689.
32. C. Genevois, M. Girard, B. Huneau, X. Sauvage and G. Racineux, "Interfacial reaction during friction stir welding of Al and Cu", Metallurgical and Materials Transactions A (2011) 2290-2295.
33. I. Galvao, J.C. Oliveira, A. Loureiro and D.M. Rodrigues, "Formation and distribution of brittle structures in friction stir welding of aluminium and copper: influence of shoulder geometry", Intermetallics 22 (2012) 122-128.